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# Orientation of Balloon-Borne Instruments

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## Abstract

Balloons have proven to be valuable platforms from which to make scientific measurements, including high resolution photography of the sun in particular. These and other astronomical observations require accurate orientation of the instrument relative to a celestial frame of reference. Appropriate sensors must be included in the orientation system to sense deviation of the instrument from the desired orientation, actuators must be provided to correct the orientation error, and a suitable gimbal system must be devised to minimize the restraint of the instrument by the balloon system.

Though the suspension system and balloon environment pose many design constraints, such as the order and configuration of the gimbals, the choices are usually compromises. Photoelectric sensors aided by inertial rate detectors used in conjunction with torque motors and three or more gimbals have proven to be a popular and effective combination.

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The orientation of a balloon-borne instrument entails the use of one, two, or three gimbals, depending on whether simple uniaxial control, biaxial pointing, or triaxial stabilization is required. Uniaxial control suffices if it is necessary only to have one side of the instrument oriented, say, toward the sun; biaxial, if the instrument, such as a telescope, must be pointed at a celestial target such as a star; and triaxial, if the target is an extended source, the image points of which must be held stationary in the focal plane of the instrument, as for high resolution photography of the moon. Uniaxial control is perhaps best exemplified by the solar azimuth-pointing platform (SAPP) shown in Figure 1. In this instance, the platform is the gimbal, the axle of which is a vertical shaft attached to the load lines of the balloon through a swivel and a universal joint and to the trapeze bar beneath, through a universal joint. This platform was built by the Ball Brothers Research Corporation for the Air Force Cambridge Research Laboratories [Dolder and Johnson, 1960] for use on long duration balloon flights to accommodate various solar instruments including a solar sextant. The upper and lower universal joints were used to decouple the platform from asymmetrical rigging of the load lines

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and asymmetrical loading of the trapeze bar, respectively. In this control system, the platform was torqued in azimuth against the trapeze bar used as a reaction wheel. Friction in the swivel and air drag on the trapeze bar prevented exceeding the maximum speed of the torque motor. A D.C. torque motor was used to drive the platform relative to the trapeze bar in a direction dictated by photoelectric solar sensors [Nidey and Stacey, 1956].

Inasmuch as the balloon may be rotating in azimuth some tens of degrees per minute, it is apparent that an azimuth gimbal such as the one used on the SAPP is a necessity in any balloon-borne orientation system. If the instrument is to be pointed at a target not on the horizon, a second gimbal is required. The second gimbal is usually an elevation gimbal as on Stratoscope I [Danielson, 1961] shown Figure 2. The orientation system for Stratoscope I was built at the University of Colorado by the author and associates for the Princeton University Observatory. The telescope was supported on a composite shaft by three bearings, as shown in Figure 3. Overconstraint of the shaft was obviated by a flexure member used as a zero-backlash universal joint. A pair of magnetic clutches were used to drive the telescope in elevation against the azimuth gimbal.

The advantages of the magnetic clutches included the absence of backlash, a twenty-fold power amplification, proportionality of torque with excitation, and independence of torque with speed of slippage. Nonetheless, with the advent of transistor amplifiers, the clutches have been supplanted by the more stable and efficient torque motor.

The azimuth gimbal in turn was driven by clutches against a reaction wheel which consisted of six batteries mounted on a rigid framework between the gimbal and the load lines. The lower separator of the multiline suspension system was coupled to the reaction wheel by a torque limiter and an aircraft universal joint. The limiter was used to avoid twisting the load lines during initial orientation in which the torque derived from the clutches could easily have exceeded the windup torque of the suspension system; and the U-joint to relax the tolerances on the distribution of the mass and the equality of the lengths of the load lines.

Though adequate control torque could have been derived directly from the suspension system, the reaction wheel was deemed necessary to maintain proper slippage of the clutches, as well as to place the torsional oscillation frequency of the reaction wheel with concomitant phase shift well below the critical bandpass of the control system. Similar considerations will in general favor the choice of a suspension system with a low torsional constant used in conjunction with a large reaction wheel. The low torsional constant in turn permits a relatively long period for the pendulum motion of the gondola beneath the balloon.

One difficulty associated with the component of the pendulum motion normal to the elevation axle is rotation of the image in the image plane of the telescope. At

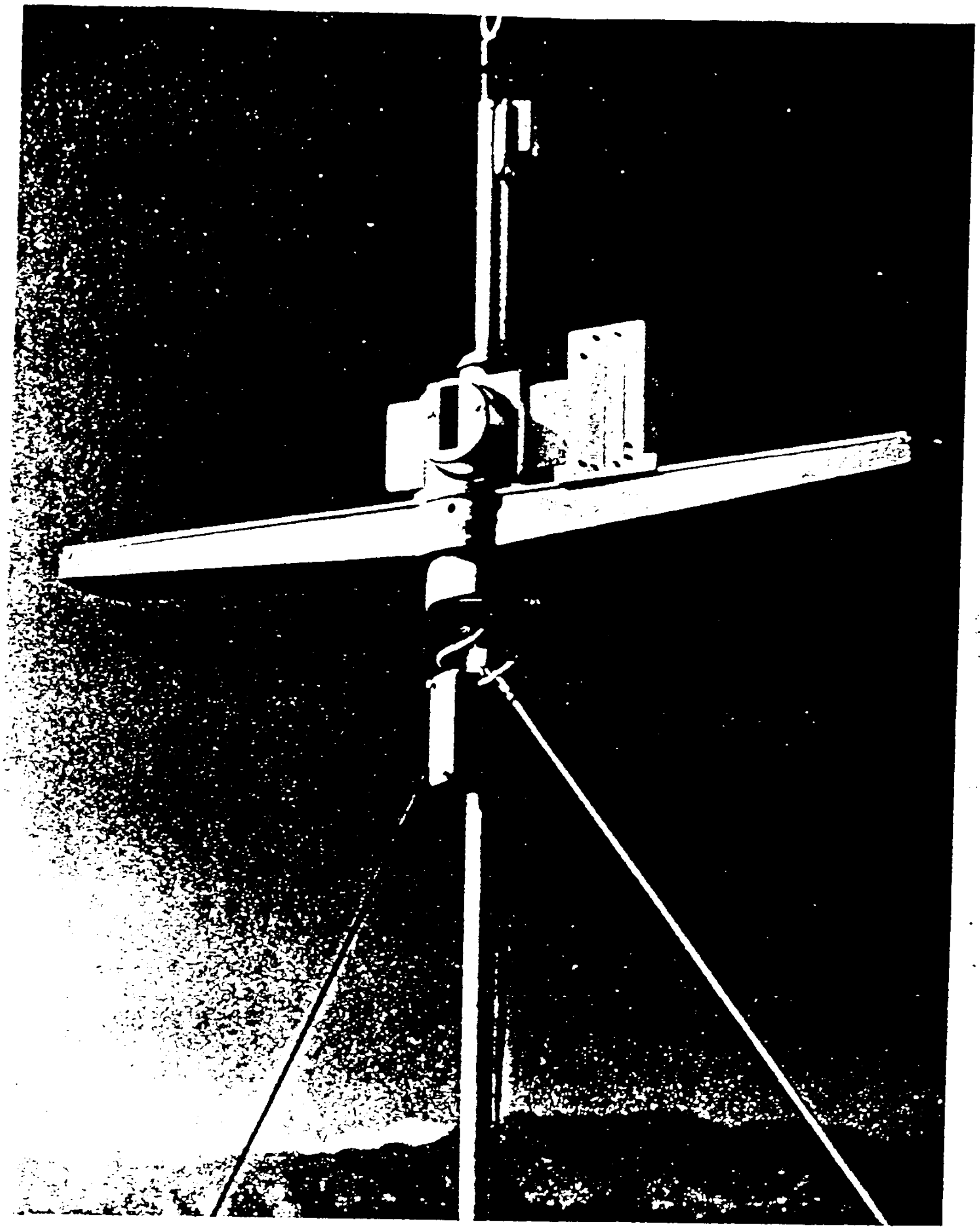

Figure 1. The Solar Azimuth-Pointing Platform
(Ball Brothers Research Corporation

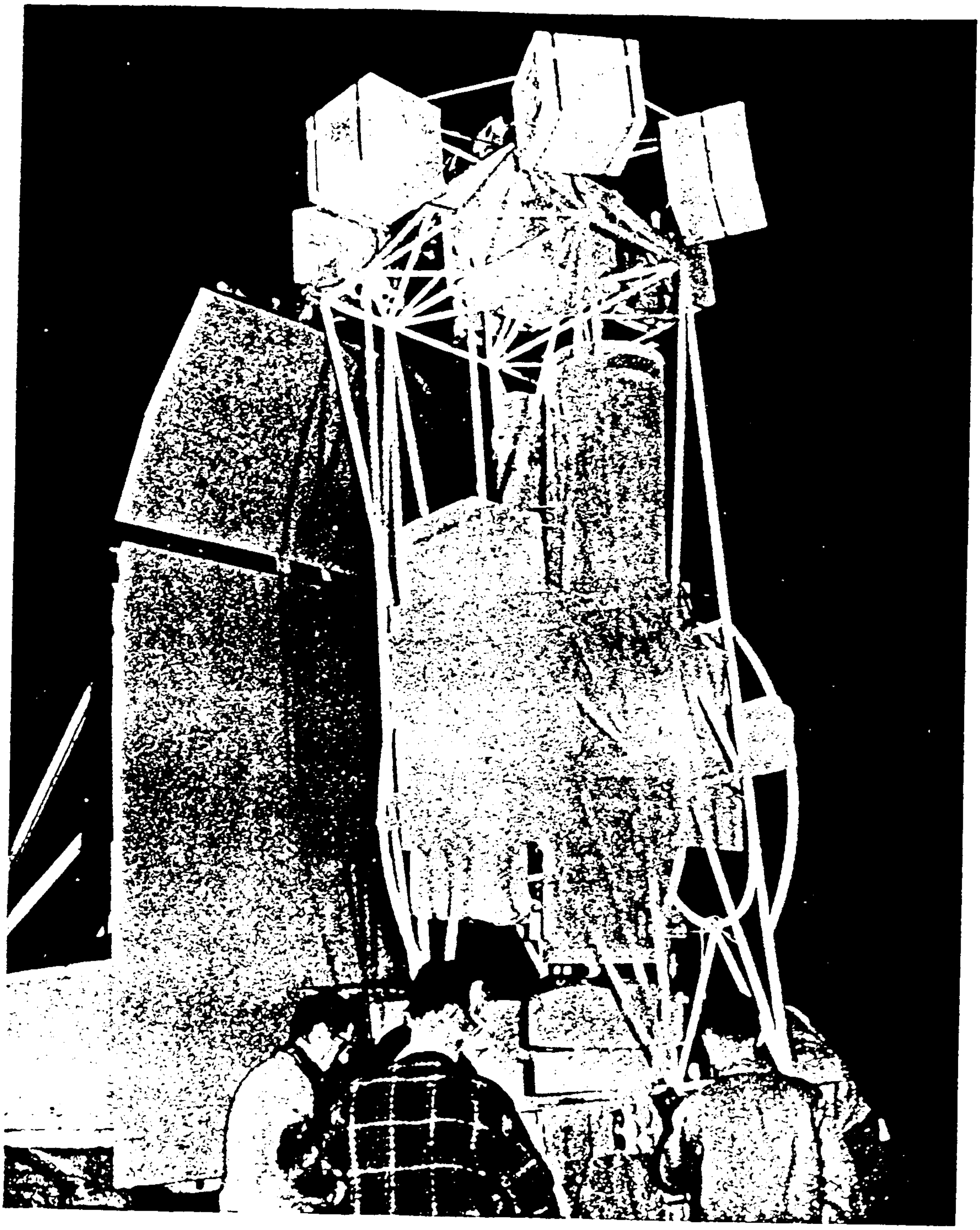

Figure 2. The Stratoscope I System
[General Mills photograph]

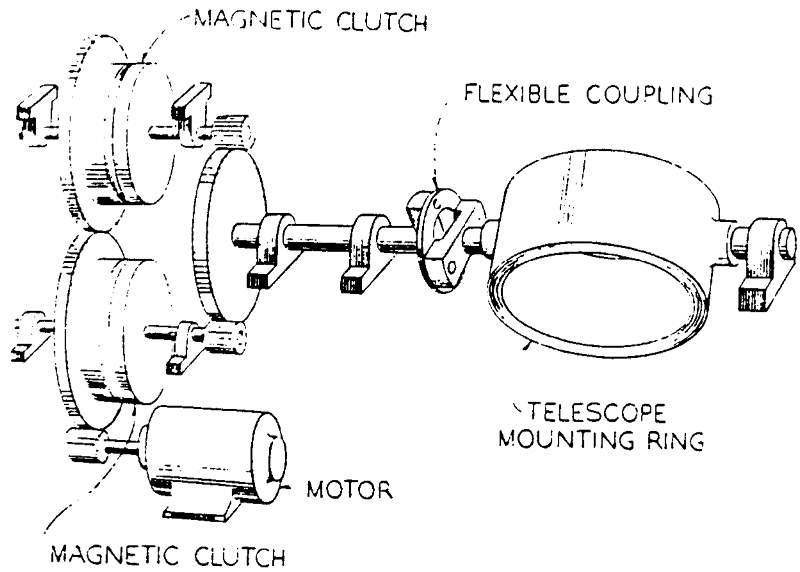


Figure 3. The Stratoscope I Elevation Shaft and Drive System

float altitude the half amplitude of the motion has been measured to be of the order of 0.1 degree or $2 \times 10^{-3}$ radians. The angular subtense of the moon is $2 \times 10^{3}$ sec of arc. Hence, if a photographic exposure of the moon were to require 10 seconds, a major fraction of the pendulum period, the maximum resolution at the limb of the moon would be 4 sec of arc, or some twelve-fold less than that obtainable on the ground.

A second difficulty is forced oscillation of the azimuth gimbal [Nidey, 1963]. The amplitude of the oscillation varies as the tangent of the altitude of the target: at 45° a 0.1° half angle pendulum motion would require an equal forced oscillation of the telescope. A third gimbal decouples the telescope from the pendulum motion; hence, obviates both the image rotation and the forcing. The third axle is usually normal to the elevation axis, making the telescope ring a cross-elevation gimbal. This gimbal arrangement is illustrated by the University of Arizona's Polariscope shown in Figure 3. One of the chief advantages of this gimbal system is that the cross-elevation axis is always normal to the axis of the telescope; and the elevation axis, nearly so. Thus, the control gain about these two axes can be adjusted to nearly the optimum value in spite of a large difference in the longitudinal and transverse moments of inertia of the instrument. Control signals for these two axes may readily be derived from a photoelectric guide telescope [Nidey, 1961] mounted collinearly with the instrument.

A single photoelectric guide telescope can produce only two independent control signals, however. Thus the control signal for the third gimbal must be derived from limit stops between the cross-elevation and elevation gimbals, a second offset guide telescope, an inertial element, the magnetic or gravitational field of the earth, or a combination of two or more of these sources. Pendulum motion of the gondola limits the accuracy obtainable from the gravitation field, whereas the magnetic field is variable with geographic position. Hence, an inertial element, such as the floated rate integrating gyroscope, torqued by signals from the limit stops or from the offset telescope, is a more effective source of the third control signal. Indeed, it may be advantageous to use an orthogonal pair of rate integrating gyros on the instrument ring to provide primary control of the elevation and cross-elevation gimbals. This is especially true if one wishes to select a number of different celestial targets by remote control. Of late, the floated gyroscopes have become available on the surplus market at a fraction of the original cost; thus, the chief remaining deterrent is the complexity of the power supplies and the control circuitry.

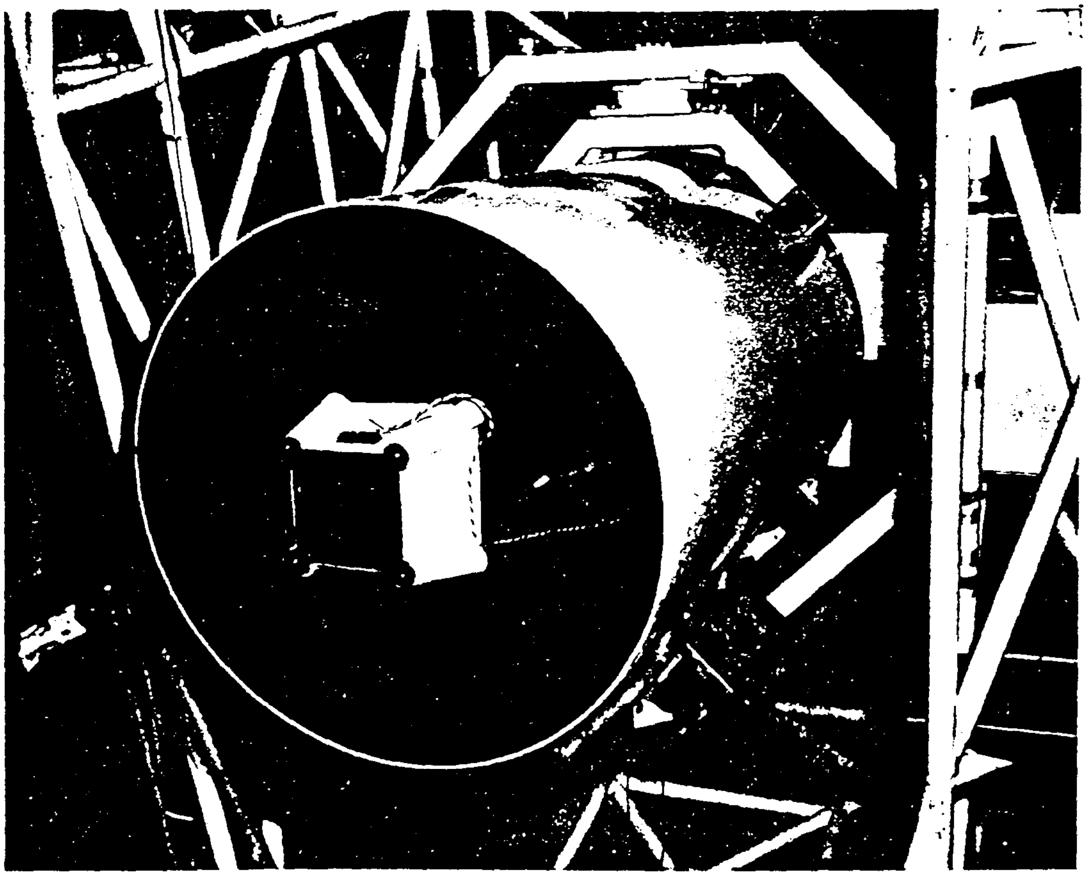

Figure 4. The Polariscope Gimbal System
[University of Arizona photograph]

With floated gyroscopes and torque motors, accuracy of control of a few seconds of arc is now being reported. The accuracy of control is limited by the sensor and by the perturbations. With a photoelectric guide telescope the former limit is set by the photon noise; that is, the random arrival of quanta at the photodetector. For a 4-inch objective telescope trained on a first magnitude star, the photon noise limit is of the order of 3 millisec of arc, assuming an integration time of 0.05 sec and average transmission and sensitivity. This limit is well beyond that currently required. The limit set by perturbations is not.

I have already mentioned the perturbation due to gimbal restraint, the forcing of the azimuth gimbal. Another perturbation is presented by the friction in the gimbal bearings. The bearing friction can be ameliorated by using floated bearings such as oil pad, pneumatic, or mercury bearings, by using flexure members, or by using dynamic bearings such as a triple race bearing, the intermediate race of which is continuously driven.

Inertial and viscous reaction in the motive element can be avoided by the proper choice of motors and by proper design of the power amplifier. Geared servomotors should be avoided, not only because of backlash, but also because of the reflected rotor inertia and back EMF. As the gondola oscillates, the rotors must be correspondingly accelerated and decelerated, necessitating inertial and viscous reactions which perturb the instrument. The viscous reaction can be minimized by designing the output stage of the power amplifier as a high impedance driver; the inertial reaction can be eliminated only by direct coupling the rotor to the gimbal. Hence, the torque motor is superior in this regard to the geared servomotor.

To avoid perturbations with translational motion of the balloon, the gimbals must all be carefully balanced. Furthermore, film transport mechanisms, and so on, must be carefully engineered to maintain balance throughout the flight and to provide counter-motion to negate inertial reactions when components are accelerated and decelerated.

Though I have used three specific systems to illustrate the principles of orientation of the balloon-borne instrument, it must be appreciated that the variations are legion. The choices of gimbals, motors and sensors can be made only by careful evaluation of the scientific objectives of the mission. It must be recognized that even the more ideal components do not combine all the desired characteristics; hence, compromises must be made.

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